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Published in:
Wear

DOI:
10.1016/j.wear.2014.12.012

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Wear 324-325 (2015) 140–146

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

A quasi-stationary approach to particle concentration and distribution in gear oil for wear mode estimation

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ARTICLE INFO

Article history:
Received 12 September 2014
Received in revised form
9 December 2014
Accepted 9 December 2014
Available online 18 December 2014

Keywords:
Break-down
Filtration
Gear oil
Particle distribution
Quasi-stationary
Wear modes

ABSTRACT

Suspension of wear particles in gear oil with respect to the diversity of particle size combined with filter mechanisms has been analyzed. Coupling of wear modes from tribology is combined with particle size bins to show how a mathematical model can be expanded to include information gained from sensors that can segment particles into size bins. In order to establish boundary conditions for the model based on real data, a filtration test is included.

Finally, the model is fitted to data from a gear in operation and differences between real data and the model are discussed.

The findings show that particles less than 14 μm dominate the wear. Hence, it is concluded that abrasion dominate the wear, for the gear in operation, and it is concluded to be in quasi-stationary mode. The distribution of the particles is observed in conjunction with the particle quantity to determine a basis for normal operation.

Limitations to the model in lack of fitting to large and frequent signal spikes are suggested to be caused by measurement equipment and/or model constraints.

Predicting the transition from quasi-stationary (normal) mode to break-down mode is made possible by particle quantity detection as well as concentration distribution.

1. Introduction

Explaining the wear generation rate of any engine from the contamination present in the lubricating oil is a way of indirectly estimating the machinery condition. A model for wear generation would have to take into account the lubrication system as well as the concentration of particles.

Prior work by Anderson, Driver and Kjer [1,2] derived equations for equilibrium conditions for unspecified small and large particles in lubricating oil. These equations showed a particle equilibrium under assumption of constant wear and constant particle removal.

Further improvement to the wear model was contributed by Szymczyk [3] introducing equations for the wear rate increase prior to machine failure. Introduction of stochastic noise to the wear generation rate equations, due to surface asperities, was described by Yan et al. [4].

In this paper we combine the work mentioned above into a single model, and add a way of calculating and simulating the wear debris in order to relate it to known wear modes for the system components.

Additions to the model are presented as ways of looking at the filter coefficient and the wear generation mechanism.

Reference and cited measurements in [1,2,4] are both based on direct reading ferrography, as described for instance by Myshkin et al. [5], Liu et al. [6] and Vähäoja et al. [7], which is able to segment metal particles as smaller or larger than 5 μm. Current techniques have progressed towards in-line measurements primarily with magnetic field sensors and optical blocking sensors, see for instance Tic [8] and Li and Zhe [9]. Both techniques have the ability of segmenting contaminants into size bins for contamination quantity investigation.

In order to relate the lubrication system theory to bin size reference measurements, an array representation of particle sizes is presented. The system differential equation for wear particle concentration rate is

$$\frac{dC}{dt} = \frac{1}{V}\left\{\frac{dM_I}{dt} + \frac{dM}{dt} + \frac{dM_F}{dt} - \frac{dM_R}{dt}\right\}, \tag{1}$$

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http://dx.doi.org/10.1016/j.wear.2014.12.012

where C is the wear particle concentration (g/m^3), V is the oil volume (m^3), M_I is the initial wear particle mass during run-in (g), M is the wear generation particle mass (g), M_F is the final particle mass (g) generated during break-down and M_R is the removed/settled particle mass (g).

A sketch of the system described by Eq. (1) can be seen in Fig. 1 where M_I, M and M_F are generated by the machinery, M_R by settling in the oil tank and filtration unit.

System assumptions follow [2] where (i) newly formed particles are spread out instantaneously throughout the oil volume, (ii) concentration of all particles is the same throughout the oil volume of interest, and (iii) the oil volume outside the oil tank is negligible.

Simulation of the system in Fig. 1 using Eq. (1) for two different particle sizes can be seen in Fig. 2. The simulation is similar to [2] where the two different curves for large and small particles are derived using different initial parameters (M_I), quasi-stationary parameters (M), break-down parameters (M_F) and filtration and settling constants M_R.

The run-in time for bearing elements and gear has been tested by Sayles and MacPherson [10] and is typically very short compared to the full lifetime for the equipment. The run-in parameters in Fig. 2 are therefore greatly exaggerated for illustration.

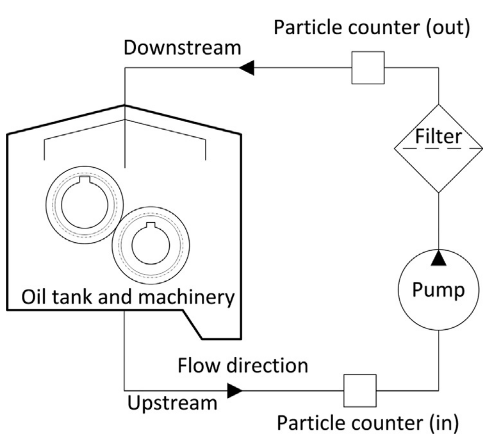

Fig. 1. Sketch of the lubricating system described by Eq. (1) including gear, pump, filter and sensors for particle counting.

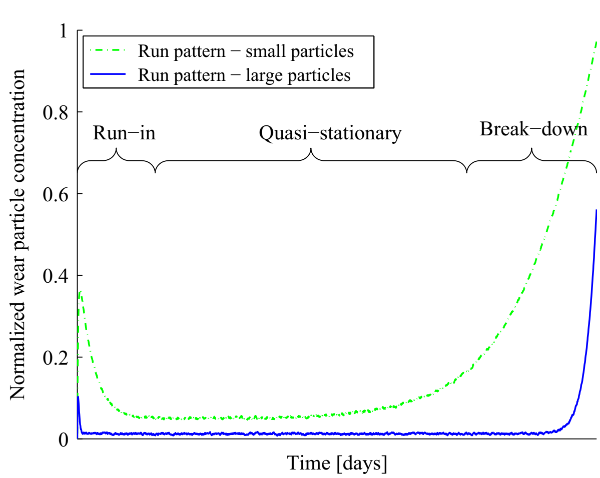

Fig. 2. Simulated system life cycle based on Eq. (1) with two sets of different parameters (small vs. large particles). ($V=1.0$; $dM_I/dt=120exp(-t/50)$; $dM/dt=10+0.05\cdot W'$; $dM_F/dt=400exp(-t/200)$; $dM_R/dt=0.99\cdot 250 * C$) for the small particles and ($V=1.0$; $dM_I/dt=10exp(-t/2.5)$; $dM/dt=1+0.04\cdot W'$; $dM_F/dt=200exp(-t/33.3)$; $dM_R/dt=0.99\cdot 250\cdot C$) for the large particles. W' is a uniform distribution of random numbers between zero and one.

Transition from quasi-stationary mode to break-down mode, as well as the break-down time, depends upon the equipment, its run conditions, and the cause resulting in the break-down pattern.

Fig. 2 simulates how a break-down pattern is expected to develop over time with small particles initially and the release of large particles relatively shortly before break-down.

We define the terminology of break-down pattern as a significant positive change in relative wear debris for one or more particle sizes. The terminology of break-down is defined as the time where damaged parts of the equipment will be overhauled/replaced or when the equipment will stop to function as designed.

A quasi-stationary wear mode model is used to determine the transition from normal operation to break-down. The main parameters for the quasi-stationary mode are wear generation and removal of particles. The rate of removal of particles, dM_R/dt, through comminution, settling, sticking to surfaces and filtration will be considered in Section 4. The wear rate, dM/dt, will be considered in Section 5.

Besides introducing an array representation for the different particle sizes, it is also well known that settling time and filtration efficiency depend upon particle size, see Winkler et. al. [11]. This implies that the filtration and settling term M_R should be modified according to particle size.

A model for the different wear modes during system operation and lifetime (from normal mechanical wear to two- and three-body abrasion, erosion, adhesion, surface fatigue), as described by Williams [12] and Raadnui [13], is implicitly incorporated into the array representation by choosing the array intervals according to the different wear particle sizes. This will be described in detail in Section 3.

2. Methodology

Introducing the modified expressions from [2–4] to each term in Eq. (1),

$$\frac{dM_I}{dt}=ae^{-t/\tau_I}, \tag{2}$$

$$\frac{dM}{dt}=P_0+W^{'}t, \tag{3}$$

$$\frac{dM_F}{dt}=be^{-(F-t)/\tau_F}+W_F^{'}t, \tag{4}$$

$$\frac{dM_R}{dt}=qkC, \tag{5}$$

where τ_I, τ_F (h), a and b (g/h) are constants determined from the initial run-in and final break-down at break-down time F respectively. P_0 is the wear generation constant (g/h) (constant wear assumed for the quasi-stationary mode). $W^{'}(t)$ and $W_F^{'}(t)$ are the stochastic nature of the wear rate generation (g/h) during quasi-stationary operation and break-down respectively. k is the filtration and settling constant (constant filtration and settling assumed), q is the oil flow (m^3/h) and C is the wear particle concentration (g/m^3).

Changing the notation to a segmentation in particle size with array notation, where multiplication is element-wise:

$$\frac{d\mathbf{M}_I}{dt}=\mathbf{a}e^{-t/\tau_I}, \tag{6}$$

$$\frac{d\mathbf{M}}{dt}=\mathbf{P}_0+\mathbf{W}'(t), \tag{7}$$

$$\frac{d\mathbf{M}_F}{dt}=\mathbf{b}e^{-(F-t)/\tau_F}+\mathbf{W}_F'(t), \tag{8}$$

$$\frac{d\mathbf{M}_R}{dt} = q\mathbf{k}\mathbf{C}, \tag{9}$$

now enables a system model that can take the varieties as explained in Section 1 into account.

Eq. (1) now becomes

$$\frac{d\mathbf{C}}{dt} = \frac{1}{V}\Big\{\mathbf{a}e^{-t/\tau_I} + \mathbf{P}_0 + \mathbf{W}'(t) + \mathbf{b}e^{-(F-t)/\tau_F} + \mathbf{W}_F'(t) - q\mathbf{k}\mathbf{C}\Big\}. \tag{10}$$

Eq. (10) can be solved analytically similar to [3,4] for each particle bin, under the assumption that each bin does not interact with another. Dependent on the system of interest, filter type and run conditions (wear modes), the constants can be determined.

3. Debris segmentation

In order to classify debris in gear oil for wear mode estimation, techniques for measuring particles are compared with definitions of tribological wear mechanisms.

3.1. Particle distribution range

The previously mentioned work all refer to ferro-analyzers (direct or by optical read-out) as reference equipment for particle estimation [4,5]. However, these measurements cannot separate the measured quantity in particle sizes (bins) and only work on ferrous particles.

Current measurement techniques that can bin particles by sizes include optical scattering, optical blocking or magnetic field sensors of ferrous and non-ferrous particles.

Scattering techniques can be applied within a narrow range of sub-micron to small micron particle sizes (0.1–10 μm) as investigated by Black et al. [14]. Measurement techniques based on optical blocking range from 4 μm up to > 70 μm (upper limit typical around 200 μm) as tested in [8], and magnetic field sensors from 50 to 1000 μm as described in [9].

3.2. Wear generation

Different wear generation modes combined with wear particle size, as described by [12,13], are shown in Table 1. Since wear particles and soft particle contaminants vary in size and shapes, segmentation of wear particle sizes are necessary when looking to combine wear modes with particle measurements.

From the size of wear particles listed in Table 1, it is concluded that sensor coverage of particle sizes from below 15 μm to above 50 μm is important in order to differentiate wear mechanisms.

3.3. Particle bins

The segmentation of particles in bins should combine the expected wear particle sizes with techniques available for measurement of particle size and quantity.

Smaller particles need to be segregated into narrower bins due to the exponential increase in quantity as illustrated in Fig. 3. The bin span (minimum–maximum particle size measured) should increase exponentially in order to somewhat counter the exponential distribution of the particles as described by Roylance and Pocock [15] and Roylance and Vaughan [16].

One segmentation for particle bins could be similar to Table 2 which to some extent follow the standard ISO 4406:1999 [17].

The importance of particle bins and their measurement range has been investigated by Lu et al. [19]. The change in particle size as a function of the wear mode supports the need for a sensor range that can measure particles in the respective particle sizes to relate measurements to the Weibull distribution, see [20].

Commercial scatter sensors for in-line measurements have a narrow measurement interval and are not expected to show the wear transition from normal to abnormal for particles of size 20 μm and larger [21]. Inductive sensors have a lower particle limit around 40–50 μm [9,22], prohibiting information of transition from quasi-stationary mode (normal) to break-down mode (abnormal).

According to Table 2 the inductive sensors actually only monitor the break-down process.

In the following, an optical blocking sensor technique is used, since the particle size sensitivity covers both the quasi-stationary wear mode and the abnormal wear (run-in/break-down) mode. Such sensors are cost-efficient and have been verified in comparative tests, see [8].

4. Filter coefficient β

The removal of particles in the system described by the term M_R in Eq. (1) is considered to include comminution, settling, sticking to surfaces and filtration.

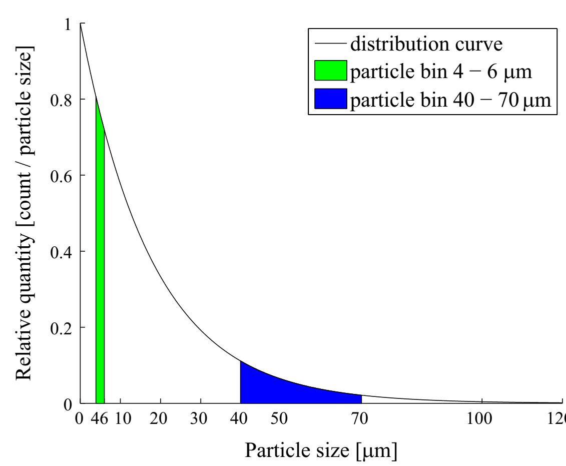

Fig. 3. Segmentation of particle bins should take into account the exponential increase in particle quantity for smaller particles. As illustrated, a more narrow range should be used for smaller particles and a more wide range for larger particles.

Table 1
Wear mechanism, wear particle types and particle sizes [13].

Wear mechanism	Wear particle type	Particle size (μm)
Abrasion	Rubbing	< 15
Abrasion	Sliding	20–50
Fatigue	Laminar	20–50
Adhesion/fatigue	Fracture	> 50
Adhesion	Severe sliding	> 50

Table 2
Particle bins, organized in relation to primary wear mode. Ranges are chosen to overlap ranges defined in ISO 4406:1999 for counters calibrated using ISO 11171:2010 [17,18].

Primary wear mode	Particle bin (μm(c))	Index
Quasi-stationary wear	4–6	4
Quasi-stationary wear	6–14	6
Quasi-stationary wear	14–25	14
Run-in, quasi-stationary wear	25–40	25
Run-in, break-down	40–70	40
Break-down	> 70	70

In this work, comminution of larger particles to smaller particles is not considered and the array notation in Eq. (10) is therefore decoupled between the different arrays.

Settling rate of particles, as described in [11], is small compared to the flow in the system. The filtration rate is therefore considered to be predominant.

Settling time is expected to influence the quantity of particles sticking to surfaces. Since settling rate is considered very small compared to the filtration rate, particles sticking to surfaces are therefore omitted in M_R.

The filter coefficient β describes a filter's performance in terms of retaining particles.

In Eq. (9), describing the settling and filtration constant, the filter performance is directly coupled to the filter and settling constant $\boldsymbol{k}$.

Using filtration efficiency as a function of particle size requires a documented efficiency from the filter supplier or a strict test in order to evaluate the β values. A commercially available filter (cellulose depth filter) has been tested using standard certified medium test dust (ISO 12103-1, A3) [23] in a setup comparable with the system illustrated in Fig. 1, with an oil volume of 0.3 m^3. The absolute filter retainability size is 3 μm and the quantity of particles has been measured during the test on the upstream as well as the downstream side by the particle sensors illustrated in Fig. 1. The nominal oil flow through the filter is 0.25 m^3/h.

The optical blocking sensors in the test measure on a partial flow ~ 0.018 m^3/h with an integration time of 120 s. The sensors are similar to the RMF CMS sensor used in [8].

The average filtration efficiency for four test runs is plotted in Figs. 4 and 5.

The $\boldsymbol{\beta}$ value is defined as

$$\boldsymbol{\beta} \equiv \frac{\text{particles}_{\text{upstream}}}{\text{particles}_{\text{downstream}}}, \tag{11}$$

where $\text{particles}_{upstream}$ is the number of particles measured in the respective bin upstream to the filter and $\text{particles}_{downstream}$ the number of particles measured in the comparable bin downstream to the filter, see Fig. 1.

The averaged $\boldsymbol{\beta}$ values from the four sequential tests can be further averaged over the measurement time to

$$\begin{aligned}\boldsymbol{\beta} &= (\beta_4, \beta_6, \beta_{14}, \beta_{25}, \beta_{40}, \beta_{70}) \\ &= (50, 190, 320, 20, 0.7, 0.4) \times 10^3\end{aligned} \tag{12}$$

where the subindex of β values refers to the particle bins index defined in Table 2.

In a full stationary mode, the graphs in Figs. 4 and 5 should resemble horizontal lines. However, the slope of the β values is mostly attributed to the decrease in system contamination during the tests. The main factor influencing the β value is primarily caused by measurement fluctuations downstream of the filter.

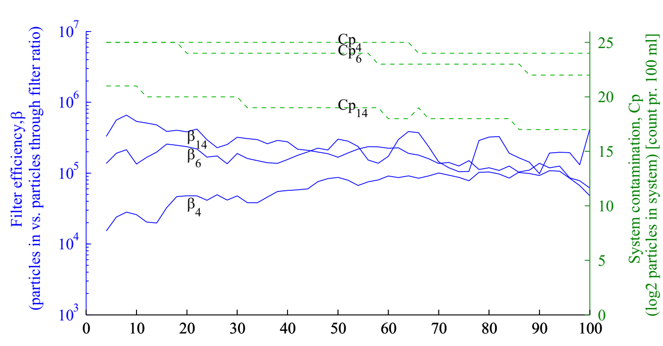

Fig. 4. Filter efficiency as a function of time and particle size (particle bin indexes 4, 6 and 14) for a commercially available filter. System contamination level indicated with green dotted lines according to standard [17]. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

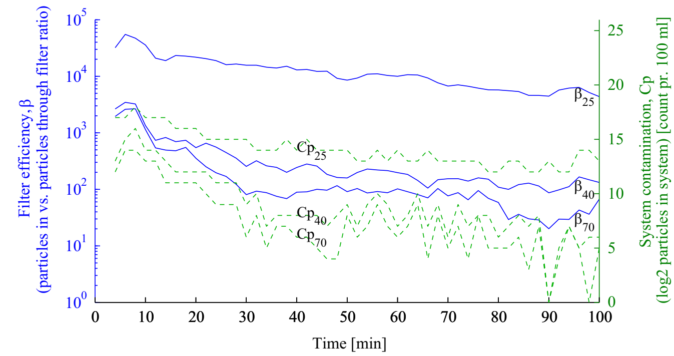

Fig. 5. Filter efficiency as a function of time and particle size (particle bin indexes 25, 40 and 70) for a commercially available filter. System contamination level indicated with green dotted lines according to standard [17]. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

The relatively large β values in Eq. (12) are a direct consequence of the standard test dust [23] specified for filtration test [18]. Test dust with this particle size distribution is retained almost completely for the measurement range by the cellulose depth filter.

For particles larger than 25 μm the initial concentration is relatively low, and during the measurement time, particle concentration approaches the calibration limit of the sensor ($C_p = 2^{10}$) within 10–20 min (5–10 measurements), see Fig. 5, on the upstream side. On the downstream side, the particle concentration is mostly below the sensor's calibration limit. Thus, measurements for particle bin indexes 25, 40 and 70 are therefore greatly affected by measurement uncertainty.

It is known from the standard ISO 16889 [24], that β values increase exponentially with particle size.

Under these assumptions the following conservative $\boldsymbol{\beta}$ values are therefore used in the model:

$$\begin{aligned}\boldsymbol{\beta} &= (\beta_4, \beta_6, \beta_{14}, \beta_{25}, \beta_{40}, \beta_{70}) \\ &= (50, 190, 320, 320, 320, 320) \times 10^3\end{aligned} \tag{13}$$

The $\boldsymbol{\beta}$ values for the test and the model can be seen in Fig. 6.

The model $\boldsymbol{\beta}$ values are used in Eq. (10) where

$$\boldsymbol{k} = \mathbf{I} - \mathbf{I}/\boldsymbol{\beta} \tag{14}$$

where $\mathbf{I}$ is an identity array. The division of $\mathbf{I}$ and $\boldsymbol{\beta}$ is elementwise.

5. Wear generation variable P_0

In Eq. (7), the wear rate is defined as a constant plus the derivative of a stochastic noise term. Since three-body abrasive wear, erosive wear and to some extent adhesive wear depend upon the presence of foreign particles, it would be reasonable to adjust the wear rate to

$$\frac{d\mathbf{M}}{\mathrm{dt}} = \mathbf{P}_0 \cdot \hat{\mathbf{C}}(t) + \mathbf{W}'(t), \tag{15}$$

where $\hat{\mathbf{C}}(t)$ is an adjusted concentration array that relates to the former particle concentration.

The wear rate of the different particle sizes might be accelerated by the total particle quantity, or a sub-array of particles and not only the respective quantity of one particle size.

One way of implementing $\hat{\mathbf{C}}(t)$ would be as a memory array that relates the system particle concentration at time (t_{n-2}) to

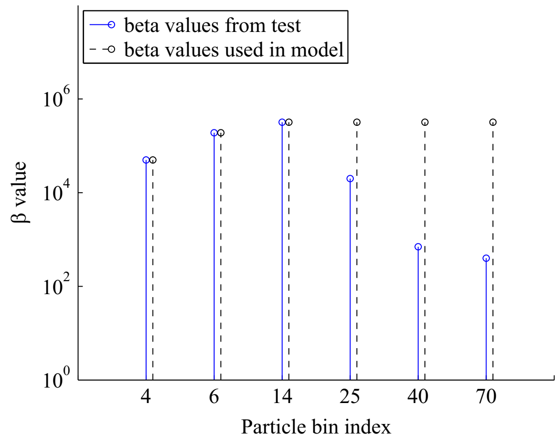

Fig. 6. The β values from test (blue full line) and the β value used in model (black dashed line) for all particle bins. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

time (t_{n-1}) in order to calculate the concentration generation $(\mathbf{P}_0 \cdot \hat{\mathbf{C}}(t))$ at time t_n.

The subscript n denotes the discrete distribution of time intervals in the measurements data. However, the model used in Section 6 does not implement the proposed memory array for the wear particles, since it is our goal to estimate whether the simple model can fit measured data.

Accordingly, $\hat{\mathbf{C}}(t)$ is an identity array in the following.

6. Results

In the following, the measured quantity (count of particles pr. 100 ml) from a gear in operation (Rolls-Royce TT 2400) onboard an anchor handling supply vessel is converted to volume density and compared to the model.

Three months of operational data is gathered from January 2014 to March 2014 and used in comparison.

The sensor used for measurement is calibrated according to ISO 11171 [18] where the measured particle area is converted to equivalent spherical diameter according to the calibration standard. To convert from particle quantity pr. 100 ml (default from the sensor) to g/m^3, the mean spherical diameter for the particle bin is used.

The approximate mean spherical diameter can be seen in Table 3.

Wear particle concentration for the gear, $\mathbf{C}_{gear}$ is defined as

$$\mathbf{C}_{\text{gear}} = \rho_{\text{steel}} \boldsymbol{V}_{\text{particle}} \boldsymbol{\Phi}_{\text{data}}, \tag{16}$$

where ρ is the mass density of steel (7850 kg/m^3), $\boldsymbol{V}_{\text{particle}}$ the particle volume pr. particle (m^3/particle) and $\boldsymbol{\Phi}_{\text{data}}$ the number of particles pr. volume (particles/m^3) from the data.

The calculation of particle concentration is based on the assumption that the main composition of the surface material of the gear is made by steel.

Model and equipment data for each particle concentration can be seen in Figs. 7 and 8. The model data (blue) is followed by equipment data (green) on an arbitrary time scale with interval of approximately 3 months, in order to illustrate the correlation between the model and data.

The equipment is estimated to be in quasi-stationary mode, which reduces Eq. (10) to

$$\frac{d\mathbf{C}}{dt} = \frac{1}{V}\{\mathbf{P}_0 + \mathbf{W}'(t) - q\boldsymbol{k}\mathbf{C}\}. \tag{17}$$

The model parameter $\mathbf{P}_0$ can be estimated from the arithmetic mean of the data. The model parameter $\mathbf{W}'(t)$ can be estimated from the standard deviation of the data.

The variations in the model are described using a random variable $\mathbf{W}'(t)$ modeled as a Gamma distribution scaled according to the standard deviation of the data.

Bin indexes 4, 6, 14, and 25 have a low frequency variation in the data whereas bin indexes 40 and 70 have a more dominant high frequency variation. The low frequency variation is likely to be caused by differences in applied gear load, ambient run condition or other external factors. The high frequency variation is to some extent explained by the model. Low frequency variation

Table 3
Relation between particle bin and mean spherical diameter used to convert gear data in count/100 ml to particle weight density. Index refers to the particle bins.

Index	Particle bin (μm(c))	Mean diameter (μm)
4	4–6	5
6	6–14	10
14	14–25	20
25	25–40	33
40	40–70	55
70	> 70	100

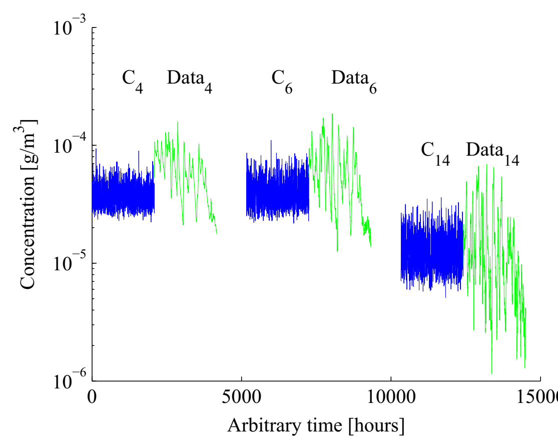

Fig. 7. Comparison of model data (blue) and gear data (green). Subscript refers to the particle bin index from Table 2. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

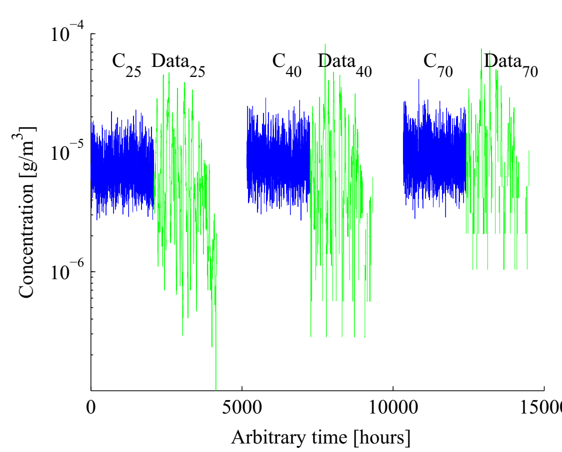

Fig. 8. Comparison of model data (blue) and gear data (green). Subscript refers to the particle bin index from Table 2. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

in bin indexes 40 and 70 is not significant due to the limited number of particle counts in these channels.

The overall decrease in concentration from bin index 4 to bin index 70 as seen in Figs. 7 and 8 is expected for an equipment in quasi-stationary operation [15,16].

The estimation parameters for the wear, $\mathbf{P}_0$, are deducted from Eq. (17) by setting the concentration rate $d\mathbf{C}/dt$ equal to zero. The result can be seen from Table 4.

The concentration density distribution for the particle bins can be informative in order to follow the progression from quasi-stationary mode towards break-down mode, or from one wear mechanism to another.

The wear particle density distribution for the measured time span of three months can be seen in Fig. 9.

The estimated wear generation parameters for the model and data in Table 4 can be compared with the proposed interpretation of primary wear modes in Table 2. The wear mode is assumed to be quasi-stationary, and from comparison between Tables 4 and 1 it can be concluded that the main wear mechanism is abrasion and almost no adhesion/fatigue.

Bin indexes 4 and 6 contribute with 74% of the total wear generation according to Table 4. It can therefore be concluded that particles less than 14 μm dominate the wear when in quasi-stationary mode.

It is possible using both the relative concentration and the density distribution to estimate transition into break-down. An increase in the total amount of particles (with the same density distribution) indicates a transition. The same is the case when a change in density distribution occurs, without altering the total amount of particles.

Table 4
Wear generation coefficients (mg pr. hour) from the model when fitted to the gear data. Index refers to the particle bins.

Index	Wear parameter $\mathbf{P}_0$ (mg/h)
4	6.1
6	5.9
14	1.6
25	0.82
40	0.87
70	0.97
Σ	16.26

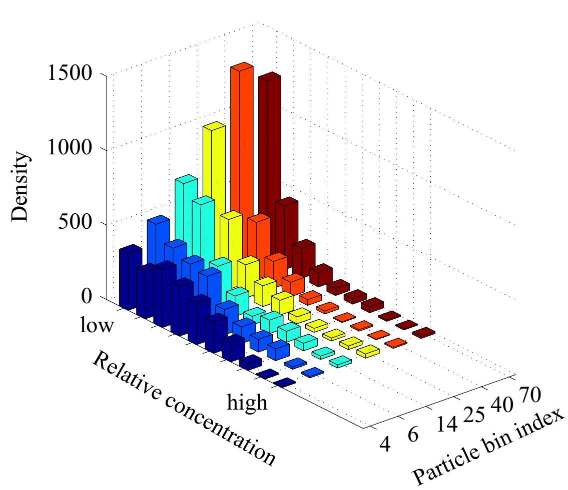

Fig. 9. Histogram of three months data for each differential particle bin index. The density distribution determines a basis for wear evaluation during the time period. A propagation in density and/or concentration determines a wear mode change.

7. Discussion

Verification of the complete model described by Eq. (10) including both run-in and break-down requires a laboratory setup with gear, oil pump and filter similar to Fig. 1 and the described sensors to segregate the particles into bins. A controlled wear generation in the laboratory gear is therefore essential in order to prove the full model.

In this work, the filter efficiency has been measured with automatic particle sensors similar to [24] where uncertainty within each bin relates to the test dust used. Improved measurements of the β values could be gained by sequential filtration tests using test dust with different particle size distributions ensuring that enough quantity in a specific bin size is present upstream the filter.

The large concentration spikes seen in Figs. 7 and 8 are not explicitly described by the model presented in this paper. These frequent signal spikes occur with changes in run condition, start or stop or a random phenomenon not included in this model.

The low frequent drift observed in Figs. 7 and 8 cannot be handled by the quasi-stationary model when the wear and filter parameters are assumed time-invariant. This time invariant assumption covering a time window of three months might simply be too long in order to fit the model to data properly. To handle this, a smaller time window could be applied and parameters evaluated for each time window.

An improvement to the model could also include knowledge on the entire system layout as well as its run sequences. In this paper, the focus has been on data from quasi-stationary run conditions with no on/off transitions for the lubricating system.

Further validation and improvement to the model could be done by including data from more than one ship or lubricating system.

8. Conclusion

Combining the knowledge of filter performance, system setup and sensors, we suggest a model able to estimate the wear generated and, to some extent, wear modes.

It has been shown that a particle concentration model can be fitted to a sensor system that segments particles into bin sizes. With the additional information gained from different particle sizes it has been shown how to correlate measurements to tribological wear. An interpretation of tribological wear modes and mechanisms from measured particle size bins has been suggested.

The coupling of tribological wear modes and mechanisms to particle bins can be used to assess the equipment's wear generation during its quasi-stationary mode. Predicting the transition from quasi-stationary mode to break-down is possible by particle quantity detection as well as concentration distribution observation.

Acknowledgements

Support to this research was provided by the Danish Ministry of Higher Education and Science through the industrial PhD programme, and the Danish Maritime Fund (Grant no. 2013-113).

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